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Numerical modeling and leakage reduction in the water distribution system of Udine

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Abstract

The paper describes the effective achievements in terms of water supply and water resources management obtained by AMGA S.p.A. within the GAP-UK Project (Interreg IV Programme). Two main issues are addressed, namely, the calibration of the numerical simulation model and the water loss reduction which has been obtained after extensive leakage identification and repair campaigns performed all over the network. In particular, the priority of leakage identification and repair has been assigned to those sectors affected by a high rate of water loss, as a result of modeling and monitoring, thus confirming some model prediction. All the identified leakages have been repaired and the effect on the global water balance of the system is evident, characterized by a minimum night flow which passed from 215 L/s down to 165 L/s.

Keywords: calibration, genetic algorithms; minimum night flow; water balance, energy saving.

1. Introduction

In many countries of the world there is an increasing evidence of inadequate water distribution systems, due to the deterioration of ageing infrastructure (especially pipes and pumps), the rapid growth of urbanization, and the statutory and contractual quality standards that have to be offered to consumers. In particular, regulatory bodies and

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water utilities are concerned about the importance of accurately assessing and controlling water losses, which may have a strong impact also on energetic costs.

In this context, the paper describes the main results obtained by GAP-UK Project ("Environmental sustainability in the use of water resources: innovative methods for the management of water distribution systems and for aquifers protection"). GAP-UK (Water Supply Management and Protection – Udine & Klagenfurt) is part of the European Territorial Cooperation Programme INTERREG IV Italy – Austria, aimed at promoting environmental protection and sustainable development thanks to cooperation between different partners of the cross-border area.

The cooperation area covers the territory of the Province of Udine and of the Province of Carinthia. The partners involved in the project are:

- Lead Partner (LP): AMGA Azienda Multiservizi S.P.A.
- Project Partner (P1): Stadtwerke Klagenfurt AG
- Associate Partner (AP2) Carniacque S.P.A.
- Associate Partner (AP3): CAFC S.P.A.
- Associate Partner (AP4): Amt der Kärntner Landesregierung

The GAP-UK project, funded by the European Regional Development Fund (ERDF) and national government grants, has two main objectives to be achieved by the end of the work (planned for September 2013): the development of innovative management methods to reduce leakage within water distribution networks and the preservation of the quality of the aquifers from which drinking water is supplied. These objectives guarantee the sustainable use of water resources. The paper is focused on the first objective and describes, on one hand, the calibration of the simulation model of the system and, on the other, the reduction of water losses obtained after leakage identification and repair.

The paper is organized as follows: section 2 describes the water distribution system and model implementation, section 3 the procedure for model calibration and the results obtained in the validation phase, section 4 the activity related to leakage detection campaigns and section 5 the water and energy savings achieved after the repairing of all identified leakages; finally, section 6 draws some concluding remarks.

2. The water distribution system of Udine

2.1. Description of the system

Udine is a city of nearly 100,000 inhabitants in the north-eastern part of Italy. Figure 1 shows the general layout of the system, characterized by 42 km of trunk mains, 15 km of city ring and 351 km of distribution lines, for a total of 408 km. Table 1 reports some relevant data of the system before the methodology was applied.

Table 1. Water balance for the distribution system of Udine in the year 2011.

	2011	(%)
Total length of the system (km)	407.3	-
Population served	99,627	-
Number of connections	10,500	-
System input volume (m^3)	12,334,977	100.00
Authorized consumption (m^3)	8,842,478	71.69
Water losses (m^3)	3,492,499	28.31
Apparent losses (m^3)	826,443	6.70
Current Annual Real Losses (m^3)	2,666,056	21.61
Unavoidable Annual Real Losses (m^3)	257,000	2.08
Infrastructure Leakage Index (ILI)	10.4	-

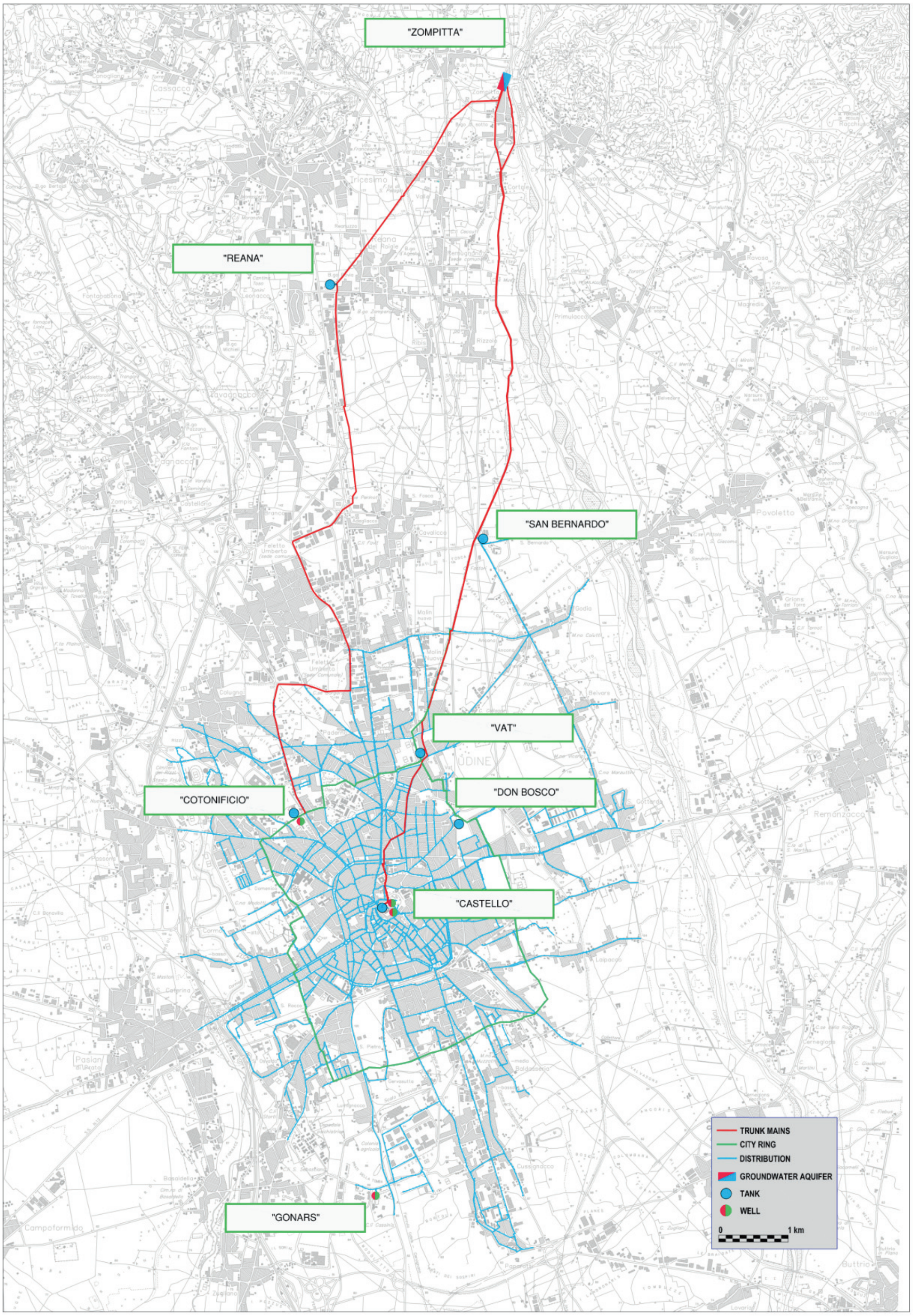

Fig. 1. Representation of the water distribution system of Udine.

2.2. Numerical model

One of the most important steps in building a decision support tool for planning future management and rehabilitation strategies is to implement an accurate simulation model, which allows to analyze the system under different scenarios. In this case, particular attention has been devoted to the geometry and topology of the network, for which a detailed representation was available: all devices such gate valves, hydrants and other fittings have been represented. The network, characterized by a total length of more than 400 km, was modeled with EPANET through 5800 nodes and 6500 pipes, including all control valves and pumping stations together with their control rules. In addition, the exact geometry of the tanks has been introduced into the model, accurately describing the volume curves of all the elevated storage tanks in the system. This allowed to obtain a faithful reproduction of their filling and emptying process during the simulations.

3. Model calibration and validation

The predictive ability of a numerical model is strongly dependent on its calibration. To this end, several measurement campaigns have been carried out both for model calibration and for its subsequent validation.

3.1. Measurement campaigns

In the calibration phase, the network had been subdivided in eleven sectors, and calibration was performed for each of these sectors. To this end, several gate valves had been closed in order to physically isolate one sector from the others, and thus ensure one or two supply points in which flow and pressure were monitored. For each sector, several pressure measurements were carried out. In total, pressures and flows were metered in more than 100 nodes and 50 links, respectively, throughout the distribution system.

Once the model was calibrated, the subsequent validation phase consisted in comparing model results with field measurements: to this end, flow measurements have been obtained from the SCADA system, while several other pressure measurements have been carried out throughout the network.

During calibration and subsequent validation measurement campaigns, we decided also to monitor flows through ultrasonic clamp-on sensors, since some magnetic flow meters installed in the system are characterized by large errors during low flows (especially during the minimum night flow interval). Interestingly, in some cases we found that reversal flow occurred at the delivery pipe of tanks.

3.2. Methodology

The calibration algorithm considers as decision variables pipes roughness and leakage coefficients (Nicolini et al. 2011). In particular, the objective function is defined as the minimization of the weighted sum of maximum absolute differences between observed and calculated values:

$$\min f_1 = W_h \max_{n,t} \left| Hm_n(t) - Hc_n(t) \right| + W_p \max_{p,t} \left| Qm_p(t) - Qc_p(t) \right| \tag{1}$$

where $Hm_n(t)$ and $Hc_n(t)$ represent, respectively, the measured and calculated head at time t in node n, while $Qm_p(t)$ and $Qc_p(t)$ the measured and calculated flow at time t in pipe p. W_h and W_p are weighting factors for heads and flows, respectively. The optimization problem is subjected to constraints defined by continuity (for every node i):

$$\sum_j Q_{ij}(t) - \alpha(t) \cdot Q_{b,i} - \ell_i(t) = 0 \tag{2}$$

and energy loss equations (for every pipe ij):

$$H_i(t) - H_j(t) = \frac{10.6668 \cdot Q_{ij}(t)^{1.852} \cdot L_{ij}}{C_{ij}^{1.852} \cdot D_{ij}^{4.871}} \tag{3}$$

In the preceding equations, $Q_{ij}(t)$ indicates the flow from node i to node j at time t; $Q_{b,i}$ is the (mean) metered consumption at node i (which can be calculated by billing information); $\alpha(t)$ is the multiplier for nodal demands depending on time, $\ell_i(t)$ the leakage at node i, which depends on pressure according to:

$$\ell_i(t) = c \; p_i(t)^{\gamma} \tag{4}$$

where $p_i(t)$ is the pressure at node i and c and γ are two coefficients quantifying the relationship between leakage and pressure. In equation 3, $H_i(t)$ and $H_j(t)$ are the total heads at nodes i and j at time t, while L_{ij}, D_{ij} and C_{ij} are the length, diameter and Hazen-Williams friction factor for pipe connecting nodes i and j, respectively.

Model calibration is based on a single-objective GA, characterized by real-coded decision variables representing pipe friction factors (according to conduit material) and the set of coefficients c (one for each sector in which the system had been subdivided) depending on the leakage.

Figure 2 shows the results in terms of comparison between measured data (green dots) and calculated values (red lines) of pressures and flows at some points in the system. Table 2 reports the comparison between measured and calculated pressure values obtained during the validation phase at some monitoring points, whose correlation plot is reported in Figure 3.

4. Leakage reduction

Leaks waste both money and a precious natural resource. The primary economic loss is the cost of raw water, its treatment and its transportation, which is often highly expensive because of the power consumed in pumping stations. Leakage leads to additional economic loss in the form of damage to the pipe network itself, e.g., erosion of pipe bedding and pipe breaks, and to the foundations of roads and buildings. Leaks also create a public health risk because of contaminants which may enter the pipe through leak openings when water pressure in the distribution system is lost. Economic constraints, concern over public health risk and the need to guarantee an effective service for all customers are the main factors that motivate water utilities to implement systematic leakage-control programs. Nowadays there are several well established procedures and modern techniques to detect where leakage is taking place in the network (Thornton et al., 2008). Each method requires the evaluation of different parameters (chemical, physical, mechanical, etc.).

Aim of the GAP-UK project was to develop an innovative and more effective water loss management method and to compare results with the methodology traditionally used to manage leaks, represented by “step testing” campaigns carried out every 4 years by AMGA S.p.A..

Step testing is a proven method of localizing water loss within a zoned distribution system. Temporarily closing gate valves allows to create small sectors (with length up to 2 kilometers). The water is taken from a hydrant located outside the area of interest and is supplied to the isolated sector through a hydrant located within the measuring zone. Since tests are mainly performed at night, a significantly lower flow rate indicates excessive leakage in the last subdivision that is shut off. Finally, leakages are pinpointed using acoustic devices (correlators and geophones). In general, sector audits are reliable, but also labour-intensive and costly.

In recent years, emerging technologies based on electro-acoustic measurements have been adopted to simultaneously reduce leakage levels and operating costs by monitoring large areas of the water network quickly and effectively. Electro-acoustic measurements, based on noise loggers, measure the intensity of noise during a pre-defined period of time. During that period, noise loggers look for the lowest noise level when no or the least possible interference is expected, typically between 2:00 AM and 4:00 AM. If such level is very low, then there is likely no leak near the noise logger. A high and consistent measured value is an evident indication of a possible leak, which is then pinpointed using correlators and geophones.

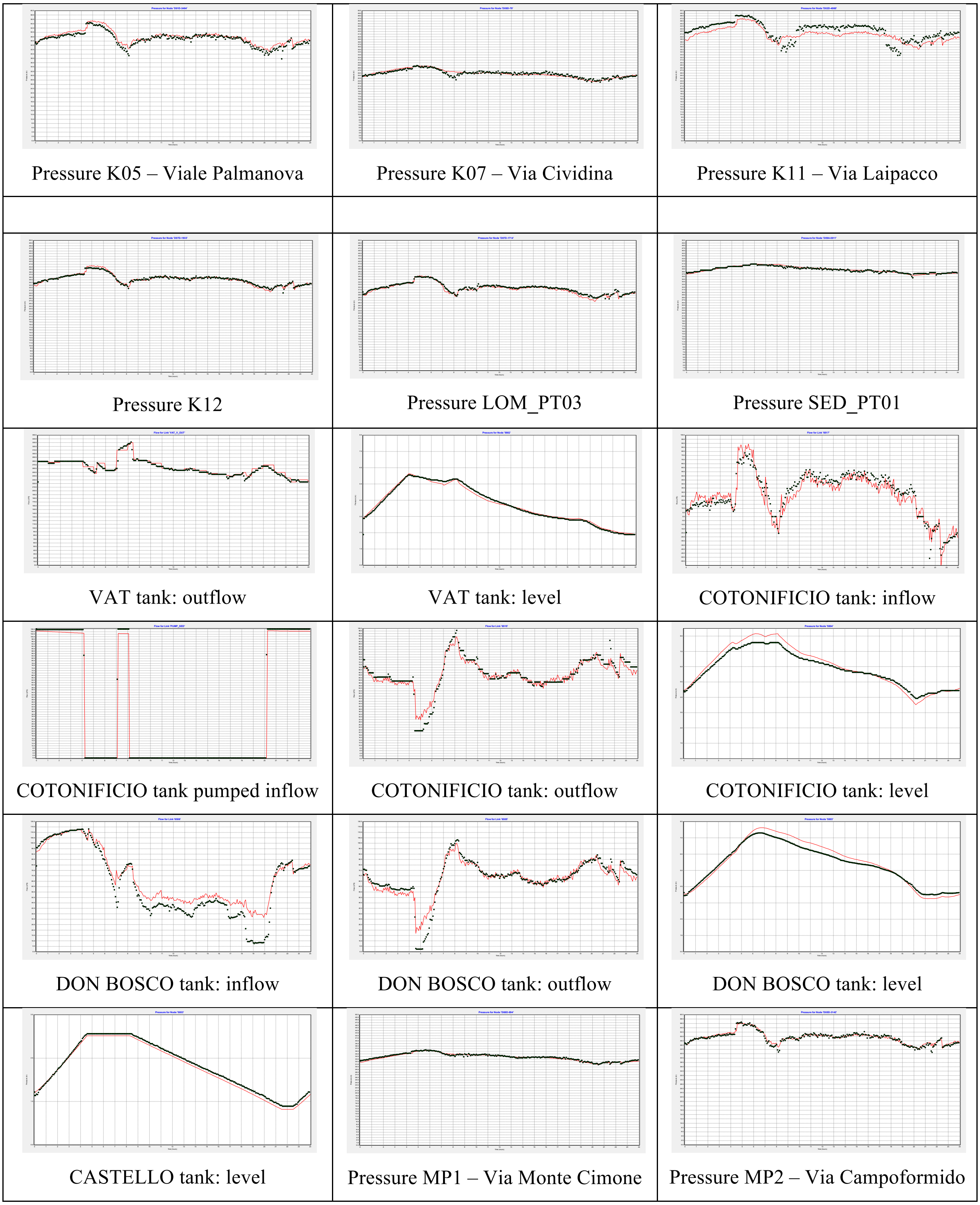

Fig. 2. Comparison of measured (green dots) and calculated (red lines) values after model calibration.

Table 2. Comparison between measured and calculated pressures at some monitoring points in the validation phase.

Junction	Measured mean (m)	Computed mean (m)	Mean error (m)	RMS error (m)
‘5803’	5.35	5.74	0.392	0.444
‘5853’	1.81	1.65	0.166	0.183
‘5804’	5.83	6.14	0.313	0.356
‘D07D-1714’	31.63	31.26	0.445	0.599
‘D09A-5811’	38.70	38.75	0.278	0.346
‘5802’	3.73	3.73	0.097	0.124
‘D08D-894’	33.80	33.66	0.257	0.312
‘D05D-3142’	49.28	49.45	0.546	0.743
‘D05D-2962’	52.16	52.08	0.451	0.616
‘D03D-409’	37.35	37.17	0.486	0.620
‘D06D-2673’	40.06	39.31	0.851	1.067
‘D01D-3464’	46.84	47.81	1.083	1.355
‘D04D-4736’	35.14	34.79	0.569	0.740
‘D09D-79’	25.77	25.78	0.473	0.623
‘D04D-5221’	37.16	36.55	0.718	0.958
‘D09D-713’	35.21	35.16	0.354	0.469
‘D02D-4060’	42.12	40.76	2.252	2.467
‘D07D-1933’	35.22	35.19	0.381	0.499

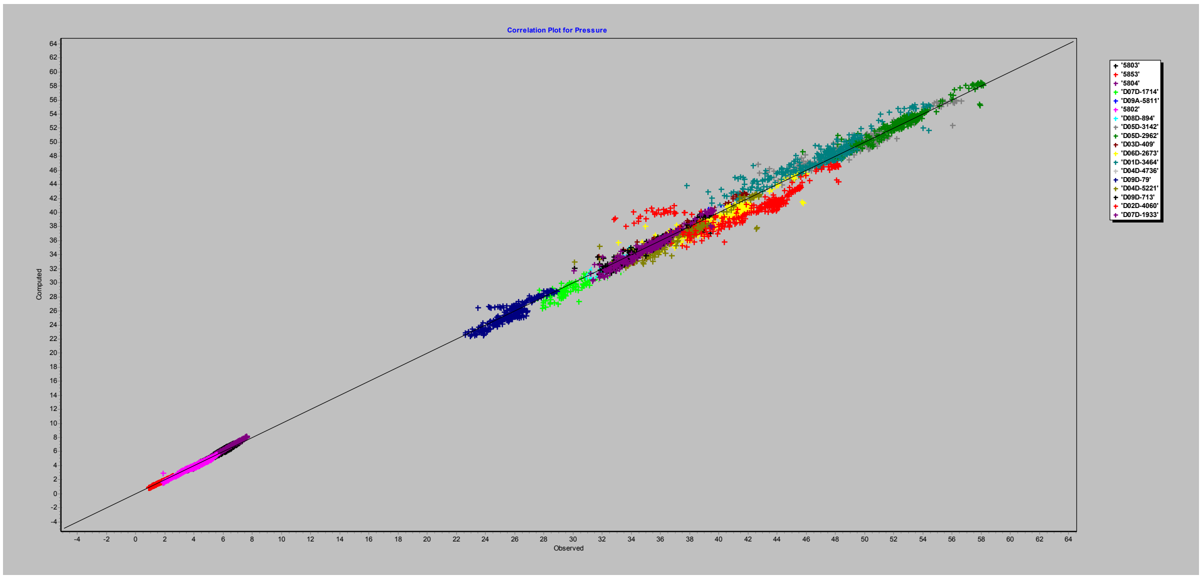

Fig. 3. EPANET correlation plot for model validation.

4.1. Leaks localization and repair

Between June and November 2012, AMGA S.p.A. carried out systematic water loss detection campaigns using noise loggers over the entire water distribution system (Table 3).

Table 3. Water loss identification campaigns during the year 2012 in Udine.

Total length of pipes analyzed (km)	360
Total number of noise logger installed	1263
Leaks detected	131
Leaks repaired	120

Leakages have occurred in different components of the distribution system: distribution pipes (26%), service connection pipes (58%), joints and valves (14%) and fire hydrants (2%). Leaks on service connection pipes include losses from damaged water meters, curb valves, connections and other devices between distribution main and property line. We found that conduits made of cast iron and asbestos cement are the most susceptible to breaks, since they are the oldest materials used in town (mainly during the 1920s and the 1930s).

Figure 4 shows the flows supplied to the distribution network in two typical days, respectively before (February 2012) and after (November 2012) leaks localization and repair. Due to the uncertainty of measurement of some instrumentation, minimum night flow (MNF) rates are considered more realistic when occurring at 3:00 AM. Table 4 reports MNF before and after leaks localization and repair.

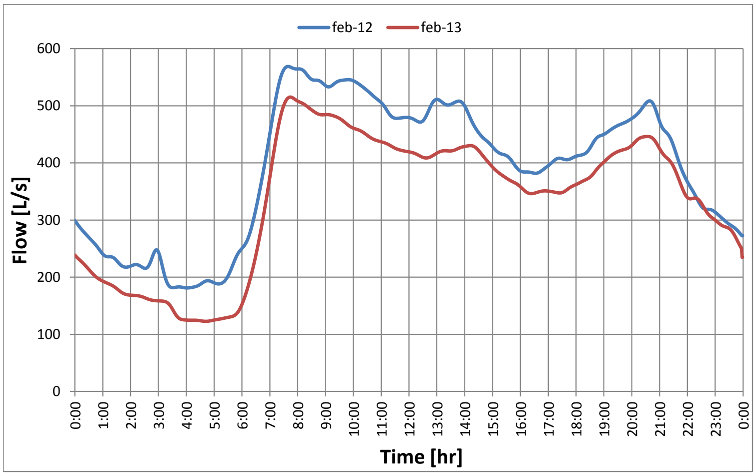

Fig. 4. Comparison between total flows supplied to the system before (in blue, feb-12) and after (in red, feb-13) the methodology.

Table 4. Minimum Night Flow (MNF) in the water distribution network

Date	MNF (L/s)
6th February 2012 2:30 AM	215.3
12th July 2012 3:00 AM	214.5
22nd November 2012 2:45 AM	164.7
10th December 2012 2:20 AM	164.0

It is clear that MNF has been significantly reduced after the water loss campaigns carried out in 2012, thus allowing a water saving (during night hours) of approximately 50 L/s. In particular, considering a conservative average reduction of 40-45 L/s, water savings consist of 1.2-1.4 millions of cubic meter per year.

This result allows to compare the water balance before and after leakage reduction. Table 5 reports the main components of the water balance for the year 2011 (see also Table 1), while the last column shows the same components which have been estimated as they would result after an average reduction of 40-45 L/s over 365 days. Infrastructure Leakage Index (ILI) is also reported, in order to compare the performance of water distribution network.

Table 5. Water balance components and ILI, calculated before and estimated after water savings achieved in 2012.

	Before 2012	After 2012
CARL – Current Annual Real Losses	2,666,056 m^3	1,115,000 m^3
UARL – Unavoidable Annual Real Losses	257,000 m^3	257,000 m^3
NRW – Non Revenue Water	28.3%	19.0%
ILI – Infrastructure Leakage Index	10.4	4.3

4.2. Comparison of methods

As discussed before, a key point of GAP-UK Project was to identify a leakage-control method more efficient than the one traditionally used, while ensuring the effectiveness in terms of water savings.

The effectiveness of the electro-acoustic method used in 2012 is not only demonstrated by the results reported in Tables 4 and 5, but it is also proved by the number and type of leakages that have been detected. During traditional step-testing campaigns, a total number of 120-140 water losses had been usually found; such value is in line with the results obtained in 2012 (Table 3).

A fundamental issue when comparing different methodologies are costs. The costs for a complete step-testing identification campaign are significantly higher than the cost of the service given by the use of noise loggers. Table 6 reports internal and external costs associated with leakage-control campaigns carried out in 2008 and in 2012. Significant savings have been achieved, especially thanks to the reduction of night-work and over-time.

Table 6. Costs associated with leakage-control campaigns carried out in Udine, respectively in 2008 and in 2012.

	Step Test Method (2008)	Electro-acoustic Method (2012)
External service costs	179 €/km	140 €/km
Internal costs	90,000 €	10,000 €
Total costs	150,000 €	60,000 €

As discussed in the previous section, water savings obtained in 2012 are in line with the ones obtained in the past. At the same time, total costs for a systematic leakage-control campaign have been more than halved. It is clear that if it is possible to reduce the cost of a systematic leakage-control campaign, the pay-back time of the investment shortens and a more efficient leakage management is possible.

5. Water and energy savings

During 2012, the simulation model has been used to rehabilitate two pumping stations, whose critical behavior has been discovered during model calibration and validation. In the same period, water savings obtained from repairing leaks have been estimated to be 1.2-1.4 million of cubic meter per year. As a result, a significant reduction of energy consumption has been achieved.

Figure 5 shows monthly energy use during 2011 and 2012: rehabilitation of pumping stations has been completed by the end of May 2012, while leakages have been repaired from September 2012 to November 2012.

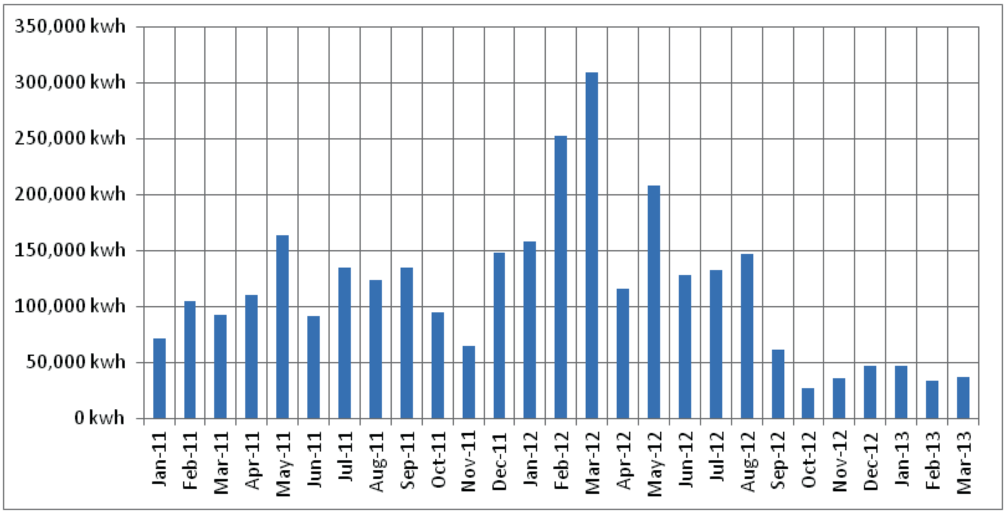

Fig. 5. Energy consumption of water pumping station in 2011 and 2012.

Table 7 shows water supplied by gravity and by pumping, together with associated energy consumption, for the last three months of years 2011 and 2012. In both periods, water supplied without pumping was almost the same (500,000 cubic meters per month). Nevertheless, the total energy consumption has been reduced by more than 50%. If we consider a medium energetic cost of 0.18 €/kWh, 36,000 € have been saved in such three months.

Table 7. Water supplied by gravity, by pumping and associated energetic costs for the last three months of 2011 and 2012

	1st Oct- 31st Dec 2011	1st Oct- 31st Dec 2012
Water supplied by gravity	1,995,000 m^3	1,988,000 m^3
Water supplied by pumping	896,000 m^3	786,500 m^3
Energy consumption	307,629 kWh	108,086 kWh

6. Concluding remarks

The paper analyzed two main issues for a real water distribution systems: model calibration and leakage management. The simulation model allowed to better analyze the behavior of the network and has been already used for pumping station rehabilitation strategies. Water loss reduction has been obtained after systematic leakage identification and repair campaigns, performed through electro-acoustic measurements. Benefits are represented by a minimum night flow which passed from 215 L/s down to 165 L/s.

Even if further work is needed in order to maintain water losses as low as possible and to keep using the simulation model as a decision support tool for system management, effective achievements have been already obtained within the GAP-UK Project (Interreg IV Programme). In particular, energy consumption for water supply has been more than halved.

The main impacts of the project, exportable to similar water systems, result in a significant reduction of operating costs and an overall better use of the water resource.

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